Army Research Laboratory

The Tactile Modality: A Review of Tactile Sensitivity and Human Tactile Interfaces

by Kimberly Myles and Mary S. Binseel

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14. ABSTRACT
Even though vision is only one modality we use to interact with our environment, most people identify it to be the most important. Hearing is also viewed as necessary for interpreting environmental stimuli. In contrast, touch, smell, and taste are largely ignored as being essential to the interaction we have with our environment. The brain seldom processes environmental information in sequence among the modalities but concurrently from several or all of the sensory modalities. Because humans have a limited capacity to receive, hold in working memory, and cognitively process information taken from the environment, the use of one sensory modality to convey information within a system can overload that modality. Multimodal systems can help to alleviate overload for any one modality, and such systems have been favorable in showing that the touch or tactile modality can be used as an independent input modality to convey information to the user or as a redundant modality to increase information prominence of the visual and auditory modalities. This review, which reflects work that occurred before mid-2006, discusses the following aspects of tactile modality: specific measures of tactile sensitivity for the human body, capabilities and limitations of tactile modality, and applications of human tactile interfaces. The review also highlights a gap in the tactile literature regarding tactile research for the head and other potential body locations.

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head tactile displays; multimodal displays; tactile displays; tactile modality; tactile sensitivity

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1. Introduction

The brain rarely processes events of the physical world using signals from one sensory modality (Oviatt & Cohen, 2000). Instead, it simultaneously processes stimuli from several or all of the sensory modalities from which we are able to interpret meaning from the surrounding environment (Moorhead, Holmes, & Furnell, 2004). For example, an individual working in a busy chemical factory may not see anything but may hear a loud boom followed by the smell of smoke. The individual is able to interpret that something has caught fire via simultaneous signals received at the ears and nose. In another example, Soldiers are engaged in a "search and find" mission and enter a building. They are greeted by a smell reminiscent of a decaying body. Initially, the Soldiers do not see the body, but the smell alerts them to what lies ahead. Finally, you are in your car, trying to find a business establishment that you have visited once before in the past. You did not have time to write detailed directions to the establishment and decide to rely on your memory to get you there. Along the way, you become confused about several turns you need to make and declare yourself lost. You drive a few more miles and are ready to stop but smell the aroma of spices. You may not know exactly where you are going but the smell of spices alerts you that you are in the correct vicinity. You remember that the establishment is within a few miles of a spice-making company so you now know you are on the right track. Most are familiar with the concept of visual landmarks in navigation but in this scenario, the aroma served as an olfactory landmark. Initially, we may not realize the importance of the touch, smell, and taste sensory modalities, but when we take the time to evaluate everyday interactions, we realize just how powerful each can be in our retrieval and understanding of environmental information.

1.1 Purpose and Scope

The purpose of this review, which reflects work that occurred before mid-2006, is to discuss the tactile modality, specifically measures of tactile sensitivity for the human body, capabilities and limitations of the tactile modality, and applications of human tactile interfaces. Compared to other areas of the body, tactile research for the head and interfaces for the head is sparse. Therefore, a secondary concern of this review is to highlight this gap in the tactile literature.

1.2 Multimodal Systems and the Tactile Modality

Using each of the five sensory modalities, humans gather information from and interact with their natural environment. When an artificial system of some type is inserted in the loop, however, we are constrained to whatever modality that system uses. A system that uses one sensory modality (i.e., unimodal system) to gather information about the environment will likely disturb the "natural" synergy with the remaining sensory modalities. Multimodal systems allow the user (to some degree) to operate "naturally" with the environment. The two most used modalities in the design of complex systems are vision and audition and are therefore frequently overloaded. A few designers interested in multimodal systems are exploring the "rich sensations" available through the skin via tactile communication and the benefits these sensations offer in connecting us to our environment (Castle & Dobbins, 2006; Cholewiak & Collins, 1991; Gemperle, Ota, & Siewiorek, 2001; Suzuki & Jansson, 2003; van Erp, Meppelink, & van Veen, 2002; van Erp & van Veen, 2001). The use of the skin as an information channel can be beneficial within a system, especially when the visual and/or auditory channels are overloaded or weakened (Raj, Kass, & Perry, 2000; van Erp, 2001; Schrope, 2001; van Erp & van Veen, 2001).

Humans have a limited capacity to receive, hold in working memory, and cognitively process information taken from the environment. Therefore, the use of one sensory modality to convey information within a system can overload that modality. When a sensory modality is overloaded with information and it is the sole input for information transfer, the user becomes incapable of processing future incoming information via that same mode, the incidence of errors will increase (Oviatt, 1999), and situational awareness (SA) and overall user performance will decrease. A system using several sensory modalities (i.e., multimodal system) to transmit information between the user and the environment will lessen the chance of any one sensory mode becoming overloaded (Oviatt, 1999). Oviatt (1999) explains that the aim of multimodal systems should be to "integrate complementary modalities to yield a highly synergistic blend in which the strengths of each mode are capitalized upon and used to overcome weaknesses in the other" (p. 74). Although a multi-sensory stimulus will not guarantee 100% detection of a stimulus, it will help to increase the probability of detection (Schnupp, Dawe, & Pollack, 2005).

In a multimodal system, the tactile modality can be used for various reasons. It can be used as an additional, independent input modality to convey information to the user or as a redundant modality to increase information prominence of the visual and auditory modalities (Sherrick & Cholewiak, 1986; Sorkin, 1987). For some visually impaired users, the tactile modality can become the primary or only input for the receipt of information. It is also ideal in situations when the operator must divide his attention among a number of tasks or when an auditory feedback system may disturb others nearby (Akamastu, MacKenzie & Hasbrouq, 1995).

A tactile system designed by the U.S. Naval Aerospace Medical Research Laboratory for military pilots is the Tactile Situation Awareness System (TSAS). The TSAS is a vest filled with 32 tactors, which is worn on the torso of a pilot. The system is not the primary source of aircraft information but is an additional, independent tactile system for conveying information to the pilot. The system communicates with the pilot via vibration signals to the skin of the torso, which are initiated by the vibrators in the vest. The system was designed in response to aircraft mishaps attributed to spatial disorientation which occurs when the pilot is unaware of his orientation in space and cannot decipher if the aircraft is heading down or up. The TSAS allows the pilot to always know his orientation with respect to the ground (Ryan, 2000). The system was designed so that the location of the vibration on the torso directly relates to the position of the aircraft (Schrope, 2001). For example, vibration applied to the front of the torso signals that a correction is needed for the front of the aircraft, and vibration applied to the left side of the torso signals that a correction is needed for the left side of the aircraft (Schrope, 2001). The system has been shown to increase pilot performance over a sole source visual cockpit indicator. The system has also been used to reduce spatial disorientation for divers and astronauts (Castle & Dobbins, 2006).

2. Basic Physiology of the Skin

The skin has an area of 1.8 m^2, a density of 1250 kg/m^3, and a weight of 5 kg (Sherrick & Cholewiak, 1986). It is classified as either glabrous (i.e., non-hairy) skin, which is found only on the plantar and palmar surfaces, or hairy skin, which is found on the rest of the body. These divisions are relevant to tactile displays because they vary in sensory receptor systems and measures of tactile sensitivity (Cholewiak & Collins, 1995). Four types of mechano-receptive fibers have been identified in glabrous skin: Meissner corpuscle (RA), Merkel cell (SAI), Pacinian corpuscle (PC), and Ruffini ending (SAII). Table 1 shows a list of specific characteristics for each fiber.

Table 1. Characteristics of the four types of mechano-receptive fibers in the human skin (adapted from van Erp & van den Dobbelsteen, 1998).

	QuicklyAdapting	**Slowly Adapting**
Superficial skin	Meissner corpuscle (RA) • small receptive field • non-Pacinian (NP) I channel, not sensitive to temperature • 10 to 100 Hz • temporal summation: no • spatial summation: yes • local vibration and perception of localized movement	Merkel cell (SAI) • small receptive field • NP III channel, sensitive to temperature • 0.4 to 100 Hz • temporal summation: no • spatial summation: no • tactile form and roughness
Deeper tissue	Pacinian corpuscle (PC) • large receptive field • P-channel, very sensitive to temperature • 40 to 800 Hz • temporal summation: yes • spatial summation: yes • perception of external events	Ruffini ending (SAII) • large receptive field • NP II channel, sensitive to temperature • 15 to 400 Hz • temporal summation: yes • spatial summation: ? • not in glabrous skin

Each mechano-receptive fiber has a specific role in the perception of vibration that extends from 0.4 to more than 500 Hz (Bolanowski, Gescheider, Verillo, & Chechosky, 1988; Cholewiak, Collins, & Brill, 2001; Gemperle et al., 2003). The Meissner corpuscles are high density fibers that are numerous in the fingertips where approximately nine nerve fibers are related to one corpuscle (Sherrick & Cholewiak, 1986). In contrast, the Pacinian corpuscles are less dense than the Meissner corpuscles, are numerous in the distal joints, and one nerve fiber is related to one Pacinian corpuscle (Sherrick & Cholewiak, 1986). Since the four fibers overlap in their absolute sensitivities, a vibration stimulus will seldom stimulate one fiber in the skin but several fibers because the energy applied to the skin will move throughout nearby skin tissues (Sherrick & Cholewiak, 1986; van Erp & van den Dobbelsteen, 1998). Within the vibrotactile literature, the fibers are grouped to describe two systems: the Pacinian system and the non-Pacinian system. The Pacinian system has a large receptive field excited by higher frequencies and the non-Pacinian system consists of a small receptive field thought to be excited by lower frequencies (Sherrick, Cholewiak, & Collins, 1990). Bolanowski et al. (1988) found that threshold sensitivities in the range of 0.4 to 500 Hz (plotted as threshold versus frequency) reveal distinctive boundaries between the two systems. One set of fibers in the non-Pacinian system exhibited no change in threshold for low frequencies (0.4 to 3 Hz). Another set of fibers in the non-Pacinian system exhibited a gradual decrease in threshold across middle frequencies (3 to 40 Hz). The Pacinian system exhibited a U-shaped function at higher frequencies (40 to 500 Hz) where maximum sensitivity occurred between 250 and 300 Hz (Bolanowski et al., 1988; Lamore & Keemink, 1988; Setzepfand, 1935; Verrillo, 1962, 1966). As these data are often reported for glabrous skin, Verrillo (1966) also reported a similar U-shaped function for hairy skin, where maximum sensitivity occurred at 220 Hz. Sherrick et al. (1990) report perceptual sensations of the non-Pacinian system as a superficial skin flutter while sensations for the Pacinian system are described as deep and diffuse.

For any system, the designer must have sufficient knowledge regarding the physical and cognitive mechanisms for the modality for which the system is intended. If the system is compatible with the capabilities and limitations of users for the chosen modality, then users are likely to be successful in retrieving and interpreting information conveyed by the system. Along the same line of reasoning, knowledge about specific skin fibers and their response characteristics when stimulated facilitate tactile systems that are compatible with the characteristics of the skin structures over which the system will be placed. According to Kandel and Jessell (1991), Meissner's corpuscles and Merkel's cells respond to touch, Pacinian corpuscles respond to vibration, and Ruffini's corpuscles respond to rapid indentation of the skin. Thus, a vibration stimulus delivered to non-Pacinian fibers but designed to evoke responses typical of Pacinian fibers (i.e., response to vibration) would produce lower threshold values than if the stimulus were directly delivered to Pacinian fibers. Likewise, stimuli for glabrous and hairy skin must be created to obtain the maximum sensitivity possible for each type of skin. Compatibility between the stimulus and the skin structure to be stimulated will yield sensitivity values closer to true threshold values.

Similar to the relationship found for the visual and auditory modalities, absolute threshold is inversely proportional to the amount of energy applied to the skin (Verrillo, 1966). Vibration is detected best on hairy, bony skin and is more difficult to detect on soft, fleshy areas of the body (Gemperle et al., 2003). In general, sensitivity decreases as one moves from distal to proximal extremities (Sherrick, Cholewiak, & Collins, 1990; van Erp & van den Dobbelsteen, 1998; Wilska, 1954) and skin impedance of the stimuli is different for different areas of the body (Sherrick & Cholewiak, 1986). All skin on the body will probably follow some of the basic characteristics mentioned, but skin on different areas of the body will not be equally acute because of differences in skin “thickness, vascularity, density, electrical conductivity, and more derived properties, such as moduli of shear and elasticity” (Sherrick & Cholewiak, 1986, p. 12-3; Weber, 1834/1978).

3. Body Site and Tactile Sensitivity

Weber’s (1834/1978) and Weinstein’s (1968) earlier research about tactile sensitivity perception provides the basis for what is currently known about tactile sensitivity for a particular body site relative to all the other body sites. Weber’s (1834/1978) research focused on obtaining two-point discrimination thresholds for various areas of the body. Using a metal compass, Weber (1834/1978) touched various areas of the skin with the two points of the compass some distance apart and recorded judgments of the distance between the two points. From his findings, Weber (1834/1978) promulgated five general propositions, of which the first two stated that (a) various parts of the touch organ are not equally sensitive to the spatial separation of two simultaneous points of contact, (b) if two objects touch us simultaneously, we perceive their spatial separation more distinctly if they are oriented along the transverse rather than the longitudinal axis of the body. In order of decreasing sensitivity for two-point discrimination, the tongue was found to be most sensitive, followed by the lips, fingers/palm, toes, and forehead. The motivating factor for Weinstein’s (1968) research resulted from unanswered questions from Weber’s work (1834/1978). Weinstein (1968) wanted to know if tactile sensitivity differed for gender and for the left and right sides of the body (for various locations on the body) using three measures of sensitivity (i.e., pressure sensitivity, two-point discrimination, and point localization). For pressure sensitivity, women were more sensitive than men and sensitivity was generally the same for both the left and right sides of the body. For specific body location, the forehead (face), trunk, and fingers were most sensitive to pressure and the lower extremities were least sensitive to pressure (figures 1 and 2). Further, the fingers, the forehead, and feet were most sensitive for two-point discrimination (figures 3 and 4), and the fingers, the forehead, and hallux[1] were most sensitive for point localization (figures 5 and 6). In an attempt to describe vibration sensitivity associated with different regions of the body, Wilska (1954) used a vibrator driven by a sinusoidal alternating current and placed it against the skin of various body regions. He found the hands and soles of the foot to be most sensitive and the gluteus region to be the least sensitive. The larynx region and the abdomen were found to be equally sensitive while threshold values were high for the head region. A summary of body site sensitivity is shown in table 2. Therefore, it does not appear to be coincidental that most of the body sites involved in tactile parameter estimation in the literature are also those areas of the body that have been previously identified as most sensitive to pressure and stimulus discrimination:

- finger, Cholewiak & Collins, 1995; Cholewiak & Collins, 1997; Goble, Collins, & Cholewiak, 1996; Horner, 1992; Lamore & Keemink, 1988; Rabinowitz et al., 1987;

[1]The hallux is the big toe.

- hand, Bolanowski et al., 1988; Cholewiak & Collins, 1995; Verrillo, 1962;
- arm, Cholewiak & Collins, 2003; Lamore & Keemink, 1988; Verrillo, 1966;
- thigh, Cholewiak & Collins, 1995;
- torso, Cholewiak, Brill, & Schwab, 2004; Cholewiak, Collins, & Brill, 2001.

Laidlaw and Hamilton (1937) also explored vibration thresholds for different regions of the body. They found significant variability in threshold measurements across participants within a particular region with specifically higher thresholds among the elderly and obese. These results are in agreement with others who also found an age-related increase in sensitivity threshold for vibration (Goble, Collins, & Cholewiak, 1996; Stuart, Turman, Shaw, Walsh, & Nguyen, 2003). For the older group of participants, Stuart et al. (2003) found an increase in sensitivity threshold for the forearm, shoulder, and cheek when compared to those of younger participants. However, sensitivity threshold for the finger was the same for both groups. This finding should not be surprising since both Weber (1834/1978) and Weinstein (1968) found this area to be most sensitive to pressure and stimulus discrimination reflecting a high receptor density and making it more resistant to loss of sensitivity with age (Stuart et al., 2003).

The ability to discriminate stimuli on the skin also varies with where the skin is located on the body. Two-point discrimination is a measure that represents how far apart two pressure points must be before they are perceived as two distinct points on the skin (Gemperle et al., 2003). This measurement will aid the designer in choosing how dense his tactile array can be, based on what part of the body the tactile display is mounted. Weinstein (1968) reported differences in two-point discrimination thresholds for different areas of the body. If tactors are placed too close together and each tactor is responsible for presenting a unique signal in the scheme of some complex, tactile pattern, the observer will perceive it as one signal and will miss the underlying message generated with the use of two signals. Two-point discrimination acuity is less than 1 mm for the fingers, 15 mm for the forehead, 35 mm for the forearm, 39 mm for the back, and 45 mm for the calf (Gemperle et al., 2003).

Also, the ability to localize stimuli on the skin varies with where the skin is located on the body. Localization is the ability to accurately identify where on the skin stimulation has occurred. Cholewiak, Brill, and Schwab (2004) investigated the vibrotactile localization accuracy for the abdomen using 12, 8, and 6 equidistant tactors, 72 mm, 107 mm, and 140 mm, respectively, arranged around the abdomen. Findings showed that the ability to correctly identify which tactor was presenting a stimulus increased as the number of tactors to identify decreased. Study participants were correct in their identification for an average of 74%, 92%, and 97% of the trials for 12, 8, and 6 tactors, respectively. They also found that when participants referenced the navel at 12 o'clock and the spine at 6 o'clock, they were better able to localize stimuli on the abdomen. Accuracy rates were much lower when such a reference was not available. This suggests that localization accuracy can be increased if a reference point is provided relative to the locations to be identified. Cholewiak and Collins (2003) found the same trend for the forearm. Sites on the forearm near the elbow were better localized than those sites farther from the elbow. When tactor spacing was increased from 25 mm to 50 mm, localization accuracy for the forearm also increased.

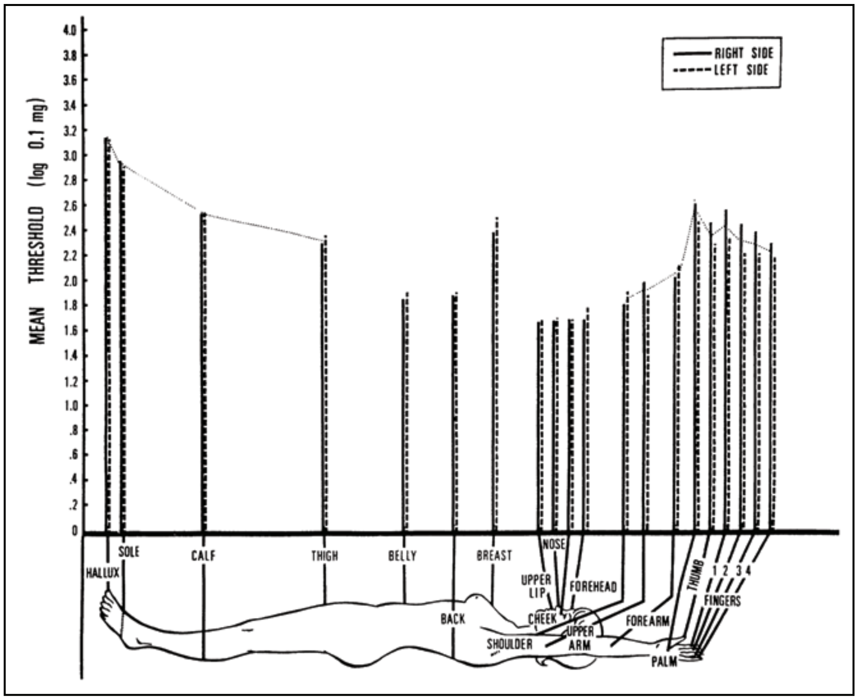

Figure 1. Pressure sensitivity thresholds for females for different areas of the body (source: Weinstein, 1968).

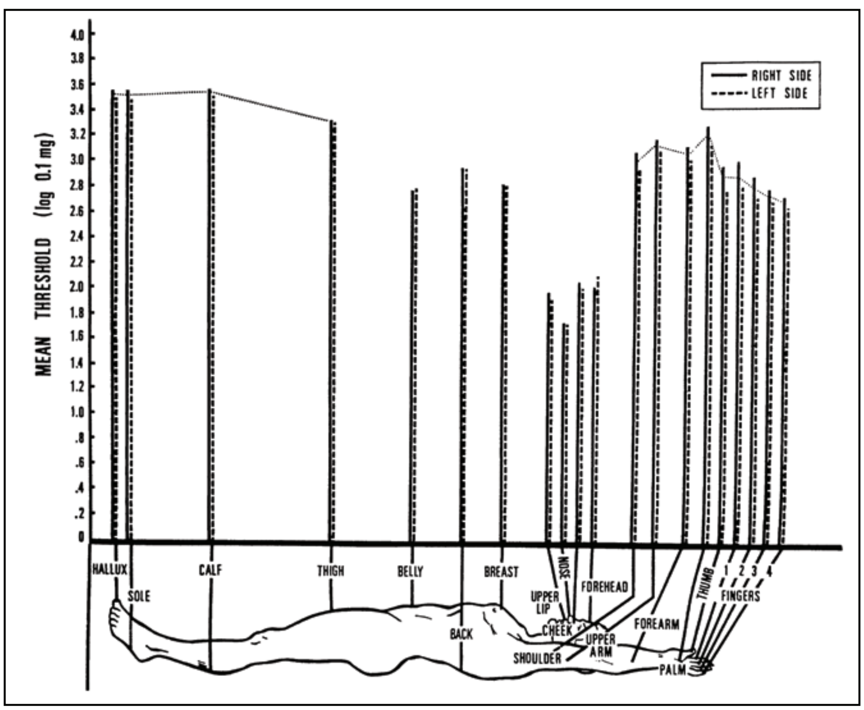

Figure 2. Pressure sensitivity thresholds for males for different areas of the body (source: Weinstein, 1968).

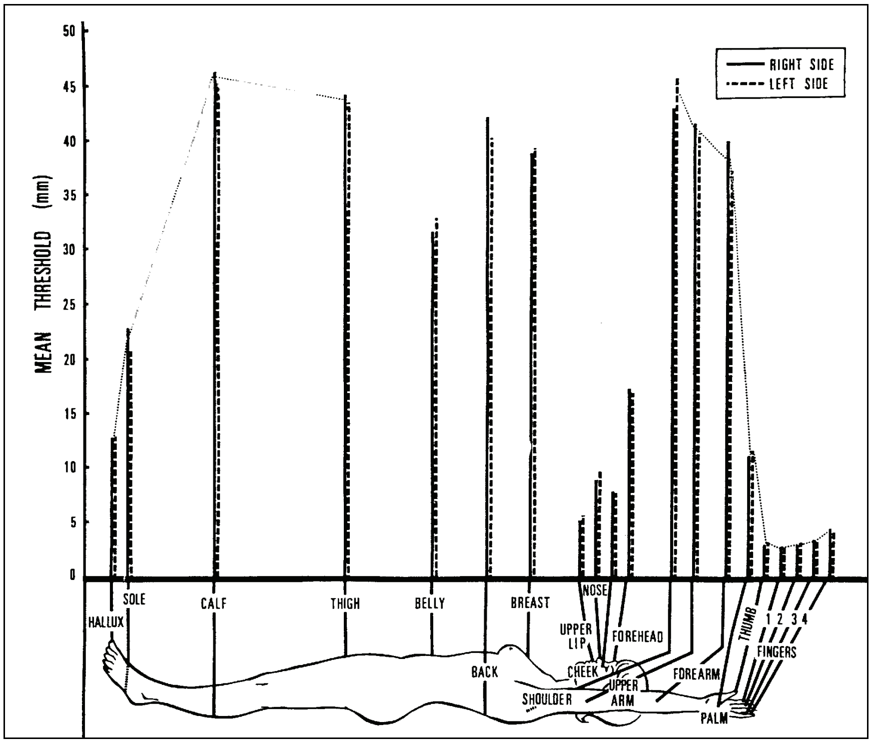

Figure 3. Two-point discrimination thresholds for females for different areas of the body (source: Weinstein, 1968).

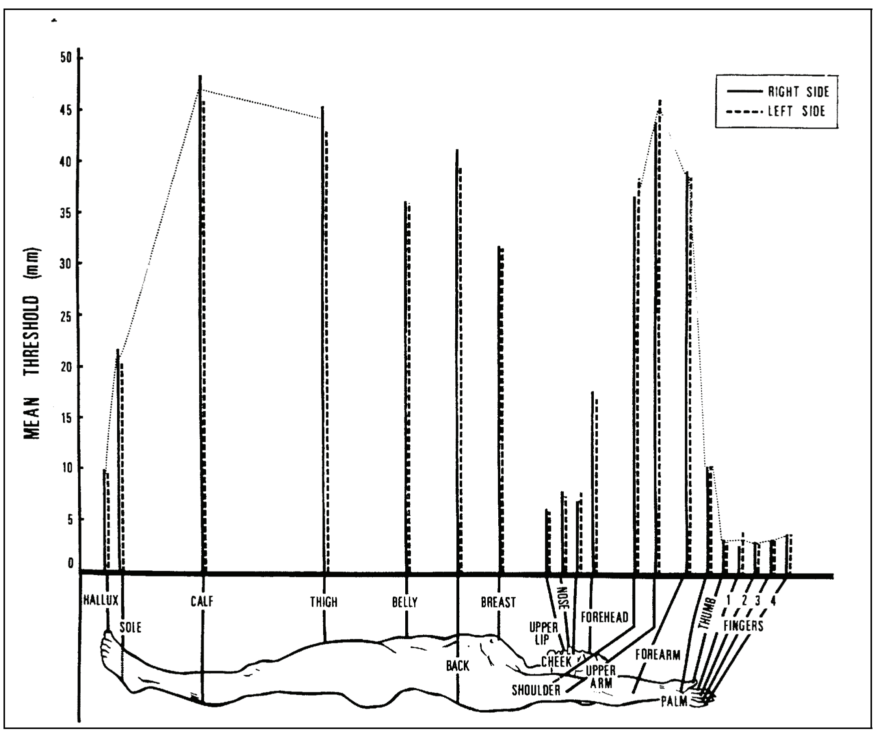

Figure 4. Two-point discrimination thresholds for males for different areas of the body (source: Weinstein, 1968).

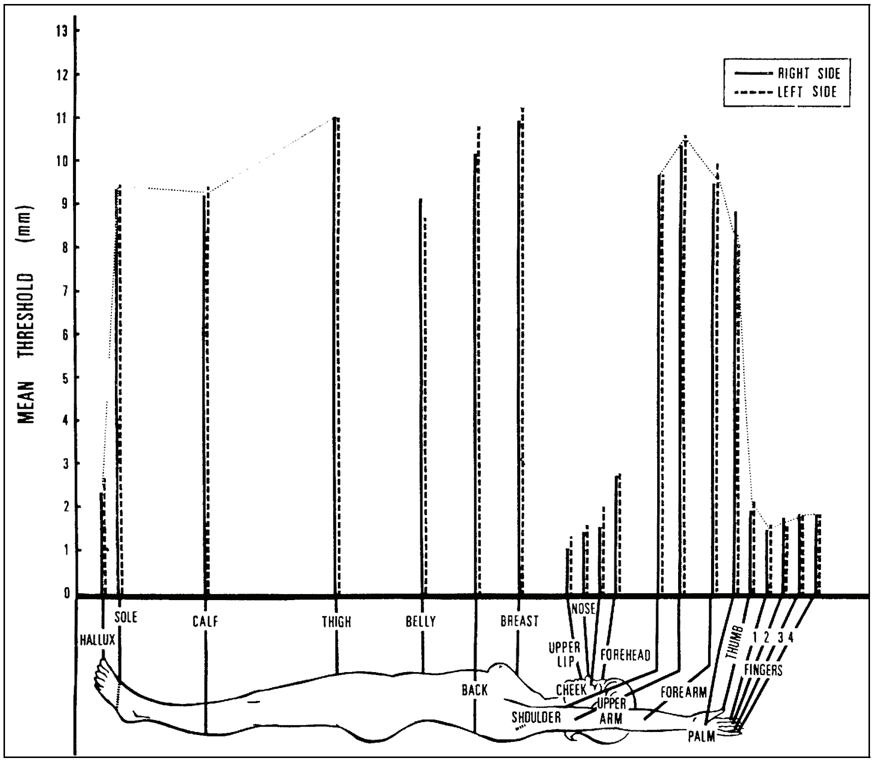

Figure 5. Point localization thresholds for females for different areas of the body (source: Weinstein, 1968).

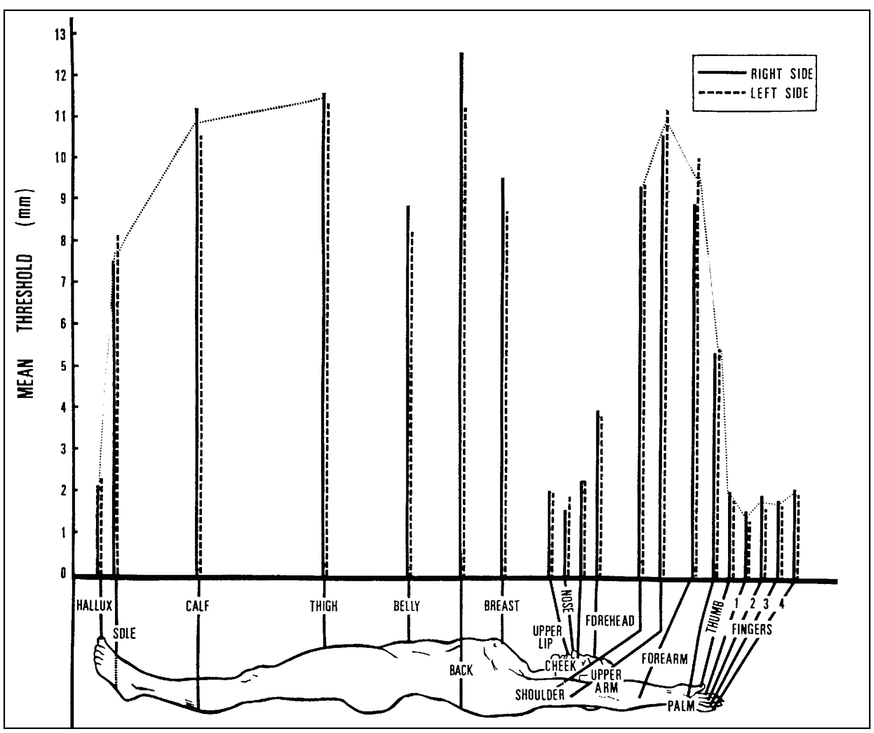

Figure 6. Point localization thresholds for males for different areas of the body (source: Weinstein, 1968).

Table 2. Body sites listed in order of most sensitive to least sensitive for tactile sensitivity measures.

Tactile Sensitivity Measures	**Body Site (listed in order of most sensitive to least sensitive)**
Pressure Sensitivity	Forehead (face), trunk, fingers, lower extremities (Weinstein, 1968)
Two-Point Discrimination	Tongue, lips, finger/palm, toes, forehead (Weber, 1834/1978) Fingers, forehead/face region, feet, arms, lower trunk (Weinstein, 1968)
Point Localization	Face region, fingers, hallux, palms, abdomen, arms, lower legs, upper chest, thigh (Weinstein, 1968)
Vibration Sensitivity	Hands, soles of feet, larynx region, abdomen, head region, gluteus region (Wilska, 1954)

4. The Tactile Signal and Sensory Limitations of the Skin

In addition to skin location, parameters of the vibrotactile signal can also influence sensitivity to and the perception of tactile stimuli. For example, the tactile threshold for the trunk is 4 microns at 200 Hz (Sherrick & Cholewiak, 1986), but this threshold may very well increase or decrease, depending on the inter-stimulus interval, amplitude, frequency, or location on the trunk (van Erp, 2002; van Erp & Werkhoven, 1999). A vibrotactile signal is defined by its frequency and amplitude (i.e., intensity). When either or both of these parameters are changed, a noticeably different sensation or feel can be imparted to the observer (van Erp & van den Dobbelsteen, 1998). Thus, information can be presented in a variety of amplitude or frequency patterns, thereby enabling multiple types of information or complex information to be conveyed. However, observers may be limited in the perception of vibrotactile signals occurring close together in time and space. Such signals are prone to spatial and temporal interactions (Sorkin, 1987) and therefore may limit the amount of information that a tactile system can present within a time interval (Schrope, 2001).

4.1 Adaptation

Adaptation occurs when a stimulus is presented for a lengthy amount of time. It is characterized by a reduction in the perceived intensity of a signal and it can occur for any stimulus. It can be avoided if stimuli are presented for shorter lengths of time (Gemperle et al., 2003). The adaptation stimulus can raise the threshold for the succeeding stimulus (van Erp & Vogels, 1998).

4.2 Masking

Masking occurs when the perception of a target stimulus is changed by a non-target stimulus that overlaps in time and/or space, and masking can interfere with one's ability to localize the target stimulus (van Erp & Vogels, 1998). Temporal masking occurs when two signals occupy the same location at different times. Spatial masking occurs when one signal is masked by another in time and not in space. Spatio-temporal masking occurs when a target stimulus is masked by another stimulus presented at the same time and location. Increased time (at least 15 ms) and space between the two stimuli will generally decrease the degree of masking (van Erp & van den Dobbelsteen, 1998).

Spatial and temporal effects can be used to create unique characteristics within a stimulus. For example, sensory saltation is a method that can be used to elicit the perception of movement on the skin. It occurs when two separate stimuli are generated from two separate sites on the skin, resulting in the perception of a series of "taps" between the two sites (Gemperle et al., 2003).

5. Application of the Tactile Modality

The largest and earliest target population for tactile displays is the visually impaired. The optical-to-tactile connector (Optacon), a reading device for the blind, was marketed in 1970 and although it is not sold any more, it is still used with success (http://en.wikipedia.org/ wiki/Optacon). The Tactile Vision Substitution System (TVSS) is a tactile system developed for the blind, which converts visual images to tactile images and presents them to the skin. The success of these systems demonstrates the potential for integrating the tactile modality into other applications. Currently, tactile systems have been found to be most efficient for the orientation, navigation, and communication domains (Castle & Dobbins, 2006). Other than the visually impaired population, the military has been one of the leading pioneers in the development and use of tactile systems. One of the first major tactile systems built and evaluated by the military is the TSAS developed for pilots to minimize the occurrence of spatial disorientation (Nordwall, 2000; U.S. Air Force, 2001; U.S. Army Aero-medical Research Laboratory, 2004). The TSAS system consists of a vest with embedded vibrators that are activated to alert the pilot when aircraft attitude excursions beyond an allowable envelope occur. The specific vibrators that are activated inform the pilot as to which direction correction in attitude needs to be made. The vest not only improved attitude compliance but also helped to ease the visual overload placed on pilots from the instruments in the aircraft. One pilot who wore the vest while blindfolded performed a few maneuvers, with no degradation in flight performance. The TSAS confirms the efficient use of tactile systems for the orientation domain. Navy SEALS[2] have shown interest in the system for under-water navigation.

The TSAS for Special Forces (TSAS-SF) was developed for the Special Forces (Chiasson, McGrath, & Rupert, 2002), and pilot tests for ground navigation found more objects were correctly identified with the TSAS-SF than with a visual display only. A similar system, the Tactor Locator System (TLS), is being used in the International Space Station (Rochlis & Newman, 2000). U.S. Army Research Laboratory (ARL) colleagues are currently working on a tactile belt for the torso designed for infantry Soldiers to aid in navigation on the battlefield (Elliott et al., 2006; Krausman & White, 2006; Redden et al., 2006; White & Krausman, 2006). The same tactile belt display is being used for research at the University of Central Florida to test the ability

[2]Sea, air, land (U.S. Navy military special forces team member)

of individuals to identify tactile signals while they undergo physiological stress similar to what the Soldier would experience during actual combat (Merlo, Stafford, Gilson, & Hancock, 2006). In addition, researchers from the U.S. Army Natick Soldier Center and the U.S. Army Research Institute of Environmental Medicine (Mahoney et al., 2006) have conducted research to examine the effects of movement and physical exertion on vigilance. Researchers used the tactile modality as a secondary communication source to the visual and auditory modes of communication. Results showed that while traversing a course with obstacles, participants covered less distance when responding to tactile signals than to auditory signals.

In non-military research, the effort is just as vigorous to design new applications for the tactile system. Schrope (2001) briefly discusses current and future work proposed for tactile displays by Hong Tan, a professor at Purdue University. Tan is working to incorporate tactile displays in suits for NASA (National Aeronautics and Space Administration) astronauts and to develop tactile displays for cars and trucks (Ho, Tan, & Spence, 2005, 2006). Research has also been under way to find ways in which tactile systems would be bene-ficial in improving the safety and efficiency of car driving (Enriquez, Afonin, Yager, & Maclean, 2001; Suzuki & Jansson, 2003; van Erp, Meppelink, & van Veen, 2002; van Erp & van Veen, 2001). Raj, Kass, and Perry (2000) and van Erp and van Veen (2001) found that presenting tactile and visual information, as opposed to visual information alone, improves performance. In addition, Gemperle, Ota, and Siewiorek (2001) report that tactile navigation displays are relevant for walking and cycling.

Akamastu, MacKenzie, and Hasbrouq (1995) showed the advantage of incorporating tactile feedback when they asked participants to locate a target using a mouse-type device and to move the cursor inside a target. After the initial visual presentation of the target, participants were given (a) no feedback, (b) auditory feedback, (c) tactile feedback, (d) color feedback, and (e) combined feedback to alert them that the cursor was placed inside the target. The authors found that the final position time of the cursor was lowest for tactile feedback and highest for the no-feedback condition, showing that the addition of tactile feedback yielded a quicker motor response for the task.

6. Tactile Communication for the Head

Although a host of objective tactile sensitivity information exists for other parts of the body, the same information is scarce for the region of the head or scalp. From Weber (1834/1978) we find that (a) the entire scalp is not equally sensitive, (b) the crown is less sensitive than the skin near the forehead, temples, and lower part of the back of the head, (c) tactors need to be placed farther apart around the crown or lower part of the skull for perception of the stimulus than they do for locations leading downward from the crown, and (d) in descending order, the hairy scalp, forehead, and temples are best for tactile acuity. Gilliland and Schlegel (1994) showed that when five tactors were placed over the parietal meridian (i.e., from ear to ear) of the head, accurate tactile detection occurred at a stimulus rate of 4 Hz. Further, as the number of tactor sites increased (i.e., 6, 8, 10, or 12 tactors), localization accuracy decreased and reaction times increased. Detection accuracy rates also increased as the study progressed, which is consistent with findings for other body parts. Hawes and Kumagai (2005) compared a head tactile system with a chest tactile system. Participants used both systems and provided subjective measurements via a questionnaire. Participants revealed a preference for the chest tactile system, stating that for the head tactile system, too much energy was applied on the head, causing discomfort and sometimes headaches. The vibrotactile transducers were set at 260 Hz for both systems. Shimizu and Wake (1982) applied continuous and discrete water-jet stimulation to the middle of the forehead and found that the perception of tactile direction is better facilitated by the use of a continuous stimulus.

Although practical, the information presented lacks the tactile psychophysical data already found for other parts of the body. For instance, there are no studies involving objective tactile sensitivity measures for the whole head as it pertains to obtaining detection thresholds for signals with varying characteristics (i.e., amplitude, frequency), localization accuracy rates, spatial and temporal resolution effects, as well as discomfort thresholds. These data are important if robust tactile systems are to be designed for use on the head and for promoting tactile guidelines in the literature that are appropriate for the head. The extent to which vibrotactile stimulation of the head is a viable method of communication and information presentation depends on determining "what" and "how much" information can be perceived on the head (Lambert, 1990).

7. Tactile Location, Display Design, and Design Guidelines

Van Erp (2002) states that current guidelines for tactile displays exist only for passive displays designed for the visually impaired. A small snapshot of tactile sensitivity research involving the fingers and hands in section 3 has successfully translated to guidelines for passive tactile displays involving the hand. In 1984 and 1985, Sherrick pondered whether the hands were the best location for processing (and perceiving) tactile signals or whether other body sites were just as suitable to support a tactile display. In discussing the requirements needed to design an (active) tactile display for the hand, Wood (1998) promotes the idea that basic (tactile sensitivity) knowledge of the hand will drive guidelines for display design. In general, the structural, functional, and sensitivity characteristics of the body location that will be involved in the operation of that system will guide system design.

Early in the discussion, we identified five body sites that have been studied extensively for tactile communication. However, because only these few body sites have been considered, the literature still lacks potential placement sites for this technology. For example, it is interesting that Weinstein (1968) found the facial region of the body to be the most sensitive to tactile stimulation, but few scientists have chosen to apply tactile stimulation to the head as a possible route for tactile communication. As designers continuously push the tactile modality as a viable solution to convey information within a system or to connect the user to his environment, unique system and user tasks will drive the search for other body site placements for tactile devices. However, unlike the hand, research in exploring the tactile modality for other sites of the body has not extensively generated design guidelines for those additional sites. Van Erp (2002) makes a first attempt to translate relevant psychophysical data into design guidelines. Psychophysical data do not automatically translate into design guidelines; however, continued extensive research will aid in narrowing and defining the data to create guidelines with well-defined contextual boundaries to facilitate their use. As more research for other body sites emerges, the need to create guidelines for tactile display design will be imperative.

8. Conclusions

As an individual interface or an additional system interface solution, the tactile modality is a viable choice for the deliverance of system information. It helps to alleviate information overload for the visual and auditory modalities. However, the placement of a tactile interface on those body locations that are often discussed in the literature may not be appropriate for a chosen application. For example, the hand is most focused upon for placement of a tactile interface because it has been identified as the most sensitive for touch. However, in many situations, the hand is otherwise occupied and therefore is not an acceptable location for a tactile interface. Such circumstances drive researchers to look to other body locations, such as the head, for placing tactile interfaces. Because a number of factors can impact tactile perception and sensitivity parameters (change in the brand of tactor, the thickness and width of a tactor, body location, the width of a surround[3], frequency, tactor indentation on the skin), further research to identify these variable effects for novel body locations is critical to defining their boundaries of use. Once the boundaries of use are defined, researchers will be able to translate the knowledge into components that are easily applicable to design interface. Such activity will not only further the use of tactile interfaces but may also help to improve and standardize the equipment used for tactile interfaces.

[3]A “surround” is a rigid surface that encloses the outer perimeter of the contactor to prevent vibration from extending to skin surfaces beyond the intended area of contact.

9. References

Akamastu, M.; MacKenzie, I. S.; Hasbrouq, T. A Comparison of Tactile, Auditory, and Visual Feedback in a Pointing Task Using a Mouse-Type Device. *Ergonomics* **1995**, *38*, 816-827.

Bolanowski, S. J.; Gescheider, G. A.; Verillo, R. T.; Chechosky, C. M. Four Channels Mediate the Mechanical Aspects of Touch. *Journal of the Acoustical Society of America* **1988**, *84* (5), 1680-1694.

Castle, H.; Dobbins, T. Tactile Display Technology: A Brief Overview of its Benefits Over Visual and Audio Displays. Ingenia, Technology and Innovation, 31-34.Retrieved on March 3, 2006 from http://www.raeng.org.uk/news/publications/ingenia/issue20/Castle.pdf (2006).

Chiasson, J.; McGrath, B. J.; Rupert, A. H. *Enhanced Situation Awareness in Sea, Air and Land Environments*. RTO HFM Symposium on "Spatial Disorientation in Military Vehicles: Causes, Consequences and Cures". La Coruna, Spain, April 15-17, 2002.

Cholewiak, R. W.; Brill, J. C.; Schwab, A. Vibrotactile Localization on the Abdomen: Effects of Place and Space. *Perception & Psychophysics* **2004**, *66* (6), 970-987.

Cholewiak, R. W.; Collins, A. A. Vibrotactile Localization on the Arm: Effects of Place, Space, and Age. *Perception & Psychophysics* **2003**, *65* (7), 1058-1077.

Cholewiak, R. W.; Collins, A. A. Individual Differences in the Vibrotactile Perception of a "Simple" Pattern Set. *Perception & Psychophysics* **1997**, *59* (6), 850-866.

Cholewiak, R. W.; Collins, A. A. Vibrotactile Pattern Discrimination and Communality at Several Body Sites. *Perception and Psychophysics* **1995**, *57* (5), 724-737.

Cholewiak, R. W.; Collins, A. A. Sensory and Physiological Bases of Touch. In M.A. Heller & W.R. Schiff (Eds.), *The Psychology of Touch* (pp. 23-60). Hillsdale, N.J.: Lawrence Erlbaum Associates, 1991.

Cholewiak, R. W.; Collins, A. A.; Brill, J. C. Spatial Factors in Vibrotactile Pattern Perception. Eurohaptics 2001 Birmingham July 2001.

Elliott, L. R.; Redden, E.; Pettitt, R.; Carstens, C.; van Erp, J.; Duistermaat, M. *Tactile Guidance for Land Navigation*; ARL-TR-3814; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

Enriquez, M.; Afonin, O.; Yager, B.; Maclean, K. A Pneumatic Tactile Alerting System for the Driving Environment. PUI, Orlando, Florida, 2001.

Foley, P.; Moray, N. *Sensation, Perception, and Systems Design*. In Salvendy, G. (Ed), Handbook of Human Factors, pp. 45-71. New York: Wiley, 1987.

Gemperle, F.; Hirsch, T.; Goode, A.; Pearce, J.; Siewiorek, D.; Smailigic, A. *Wearable Vibro-Tactile Display*. Carnegie Mellon Wearable Group, Carnegie Mellon University, 2003.

Gemperle, F.; Ota, N.; Siewiorek, D. Design of a Wearable Tactile Display. *In Proceedings of the Fifth International Symposium on Wearable Computers*, Zurich, Switzerland. http://www.wearablegroup.org (2001).

Gilliland, K.; Schlegel, R. E. Tactile Stimulation of the Human Head for Information Display. *Human Factors* **1994**, *36* (4), 700-717.

Goble, A. K.; Collins, A. A.; Cholewiak, R. W. Vibrotactile Threshold in Young and Old Observers: The Effects of Spatial Summation and the Presence of a Rigid Surround. *Journal of the Acoustical Society of America* **1996**, *99* (4), 2256-2269.

Hawes, V. L.; Kumagai, J. K. *Examination of Head And Chest Located Tactile Information for Infantry Wayfinding*; DRDC Toronto CR-2005-042; Toronto, Ontario, Canada: Department of National Defence, Defence Research and Development Canada-Toronto, 2005.

Ho, C.; Tan, H.Z.; Spence, C. The Differential Effect of Vibrotactile and Auditory Cues on Visual Spatial Attention. *Ergonomics* **2006**, *49* (7), 724-738.

Ho, C.; Tan, H.Z.; Spence, C. Using Spatial Vibrotactile Cues to Direct Visual Attention in Driving Scenes. *Transportation Research* **2005**, Part F 8, 397-412.

Horner, D. T. The Effects of Complexity on the Perception of Vibrotactile Patterns Presented to Separate Fingers. *Perception & Psychophysics* **1992**, *52* (2), 201-210.

Kandel, E. R.; Jessell, T. M. *Touch*. In E. R. Kandel, J. H. Schwartz, T. M. Jessell (Eds.), Principles of Neural Science, 3rd ed. (pp. 349-414). New York: Oxford University Press, 1991.

Krausman, A.; White, T. L. *Detectability of Vibrotactile Patterns While Performing Combat Assault Maneuvers*; in review; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

Laidlaw, R. W.; Hamilton, M. A. Bulletin of the Neurological Institute of New York, 6, 494. Cited in Wilska, A. (1954). On the vibrational sensitivity in different regions of the body surface. *Acta Physiologica Scandinavica* **1937**, *31*, 285-289.

Lambert, M. E. *The Effects of Site Configuration on a Tactile Information Display for the Human Head*; Report AFIT/CI/CIA-90-067; AFIT/CI Wright-Patterson AFB OH. Thesis. University of Oklahoma, 1990.

Lamore, P.J.J.; Keemink, C. J. Evidence for Different Types of Mechanoreceptors from Measurements of the Psychophysical Threshold for Vibrations under Different Stimulation Conditions. *Journal of the Acoustical Society of America* **1988**, *83* (6), 2339-2351.

Mahoney, C. R.; Hirsch, E.; Hasselquist, L.; Lesher, L. L.; Lieberman, H. R. *The Effects of Physical Exertion on Soldier Vigilance*; in press; Aviation, Space, and Environmental Medicine Special Supplement, 2006.

Merlo, J. L.; Stafford, S.; Gilson, R.; Hancock, P.A. The Effects of Physiological Stress on Tactile Communication. *Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting*, October 16-20, 2006.

Moorhead, I. R.; Holmes, S.; Furnell, S. Understanding Multisensory Integration for Pilot Spatial Orientation. Centre for Human Sciences, QinetiQ. European Office of Aerospace Research and Development, 2004.

Nordwall, B. D. Vest Enables Pilots to Feel Aircraft Attitude. *Aviation Week & Space Technology* **2000**, *15*2 (17), 69-70.

Oviatt, S. Ten myths of Multimodal Interaction. *Communications of the ACM* **1999**, *42* (11), 74-81.

Oviatt, S.; Cohen, P. Multimodal Interfaces that Process What Comes Naturally. *Communications of the ACM* **2000**, *43* (3), 45-53.

Rabinowitz, W. M.; Houtsma, A.J.M.; Durlach, N. I.; Delhorne, L. A. Multidimensional Tactile Displays: Identificatin of Vibratory Intensity, Frequency, and Contactor Area. *Journal of the Acoustical Society of America* **1987**, *82* (4), 1243-1252.

Raj, A. K.; Kass, S. J.; Perry, J. F. Vibrotactile displays for improving spatial awareness. *Proceedings of the IEA 2000/HFES 2000 Congress*, 181-184, 2000.

Redden, E. S.; Carstens, C. B.; Turner, D. A.; Elliott, L. R. *Localization of Tactile Belt Signals as a Function of Tactor Operating Characteristics*; in review; U. S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

Rochlis, J. L.; Newman, D. J. A Tactile Display for International Space Station (ISS) Extravehicular Activity (EVA). *Aviation, Space, and Environmental Medicine* **2000**, *71* (6), 571-578.

Ryan, D. M. Pilots: Close your Eyes and Fly! Navy Medicine. May-June, 2000.

Schnupp, J.W.H.; Dawe, K. L.; Pollack, G. L. The Detection of Multisensory Stimuli in an Orthogonal Sensory Space. *Experimental Brain Research* **2005**, *162*, 181-190.

Schrope, M. Simply Sensational. New Scientist, 2 June, 30-33, 2001.

Setzepfand, W. Zoo Biology, 96, 236. Cited in Wilska, A. (1954). On the vibrational sensitivity in different regions of the body surface. *Acta Physiologica Scandinavica* **1935**, *31*, 285-289.

Sherrick, C. E. Basic and Applied Research on Tactile Aids for Deaf People: Progress and Prospects. *Journal of the Acoustical Society of America* **1984**, *75* (5), 1325-1342.

Sherrick, C. E. Touch as a Communicative Sense: Introduction. *Journal of the Acoustical Society of America* **1985**, *77* (1), 218-219.

Sherrick, C. E.; Cholewiak, R. W. *Cutaneous Sensitivity*. In K. Boff, L. Kaufman, & J.L. Thomas (Eds.), Handbook of Perception and Human Performance, pp. 12-1 – 12-58. New York: Wiley, 1986.

Sherrick, C. E.; Cholewiak, R. W.; Collins, A. A. The Localization of Low- and High-Frequency Vibrotactile Stimuli. *Journal of the Acoustical Society of America* **1990**, *88* (1), 169-179.

Shimizu, Y.; Wake, T. Tactile Sensitivity to Two Types of Stimulation: Continuous and Discrete Shifting of a Point Stimulus. *Perceptual and Motor Skills* **1982**, *54*, 1111-1118.

Sorkin, R. D. *Design of Auditory and Tactile Displays*. In G. Salvendy (Ed.), Handbook of Human Factors, pp. 549-576. New York: Wiley, 1987.

Stuart, M.; Turman, A. B.; Shaw, J.; Walsh, N.; Nguyen, V. Effects of Aging on Vibration Detection Thresholds at Various Body Regions. *BMC Geriatrics* **2003**, *3* (1), http://www.biomedcentral.com/1471-2318/3/1.

Suzuki, K.; Jansson, H. An Analysis of Driver's Steering Behaviour during Auditory or Haptic Warnings for the Designing of Lane Departure Warning System. *JSAE Review* **2003**, *24*, 65-70.

United States Air Force. *Operational Assessment of the Tactile Situational Awareness System*; AFSOC Project 99-060. Hurlburt Field, FL, 2001.

United States Army Aeromedical Research Laboratory. *Tactile Situation Awareness System Flight Demonstration Final Report*; USAARL Report No. 2004-10; Fort Rucker, AL, 2004.

van Erp, J.B.F. Guidelines for the Use of Vibro-Tactile Displays in Human Computer Interaction. *In Proceedings of Eurohaptics 2002* (pp.18-22). Edinburgh: University of Edinburgh, 2002.

van Erp, J.B.F. *Effect of Timing Parameters on the Vibrotactile Spatial Acuity of the Torso*; TNO-report TM-01-A061; Soesterberg, The Netherlands: TNO Human Factors Research Institute, 2001.

van Erp, J.B.F.; Meppelink, R.; van Veen, H.A.H.C. *A Touchy Car*; TNO-report TM-02-B001; Soesterberg, The Netherlands: TNO Human Factors Research Institute, 2002.

van Erp, J.B.F.; van den Dobbelsteen, J. J. *On the Design of Tactile Displays*; TNO-report TM-98-B012; Soesterberg, The Netherlands: TNO Human Factors Research Institute, 1998.

van Erp, J.B.F.; van Veen, H.A.H.C. Vibro-Tactile Information Presentation in Automobiles. *In Proceedings of Eurohaptics 2001* (pp.99-104). Edinburgh, University of Edinburgh, 2001.

van Erp, J.B.F.; Vogels, I.M.L.C. *Vibrotactile Perception: A Literature Review*; TNO-report TM-98-B011; Soesterberg, The Netherlands: TNO Human Factors Research Institute, 1998.

van Erp, J.B.F.; Werkhoven, P. J. *Spatial Characteristics of Vibro-Tactile Perception on the Torso*; TNO-report TM-99-B007; Soesterberg, The Netherlands: TNO Human Factors Research Institute, 1999.

Verrillo, R. T. Investigation of Some Parameters of the Cutaneous Threshold for Vibration, *The Journal of the Acoustical Society of America* **1962**, *34* (11), 1768-1773.

Verrillo, R. T. Vibrotactile Thresholds for Hairy Skin. *Journal of Experimental Psychology* **1966**, *72* (1), 47-50.

Weber, E.H. The Sense of Touch (De Tactu. H.E. Ross and Der Tastsinn, D.J. Murray, Trans.). New York: Academic Press, 1978 (original works published in 1834).

Weinstein, S. *Intensive and Extensive Aspects of Tactile Sensitivity as a Function of Body Part, Sex, and Laterality*. In D.R. Kenshalo (Ed.), *The Skin Senses* (pp.195-222). Springfield, IL: Charles C. Thomas, 1968.

White, T. L.; Krausman, A. *Detectability of Vibrotactile Signals in Moving Vehicles*; in review; U.S. Army Research Laboratory: Aberdeen Proving Ground, MD, 2006.

Wilska, A. On the Vibrational Sensitivity in Different Regions of the Body Surface. *Acta Phys. Scandinav* **1954**, *31*, 285-289.

Wood, D. Tactile Displays: Present and Future [Editorial]. *Displays* **1998**, *18*, 125-128.

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